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CONSTITUTIVE MODELING FOR SINGLE CRYSTAL SUPERALLOYS*

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INTRODUCTION

The inelastic response of single crystal γ/γ' superalloys is quite different from the behavior of polycrystalline nickel base superalloys. Upto a critical temperature the yield stress of single crystal alloys is a function of the material orientation relative to the direction of the applied stress and the material exhibits significant tension/compression asymmetry [1]. This behavior is primary due to slip on the octahedral slip system. Above the critical temperature there is a sharp drop in the yield stress, cube slip becomes more predominant and the tension/compression asymmetry is reduced. Similar orientation and tension/compression asymmetry is observed in creep and secondary creep above the critical temperature is inferred to occur by octahedral slip [2]. There are two exceptions to this behavior. First loading near the [111] orientation exhibits cube slip at all temperatures, and; second, loading near the [001] orientation produces only octahedral slip at all temperatures.

LEVEL I CONSTITUTIVE MODEL

Earlier in the grant period, a constitutive model and finite element was developed for Rene N4 and verified using published results near the critical temperature [3].

In summary, the constitutive model is based on separating the total global strain into elastic and inelastic components. The elastic strains are calculated using cubic symmetry. The inelastic strain rate is calculated by summing the contributions of each slip system. The inelastic

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slip rate on each slip system is computed from a local inelastic constitutive equation that depends on local resolved shear stress components in each slip direction and local state variables. The orientation dependence and tension/compression asymmetry was incorporated using the "core width effect" proposed by Lall, Chin and Pope [4]. The constitution model for local slip also is based on a system of state variables to model the drag stress. Back stress was not included since this typically is associated with dislocation pile-ups at obstacles like grain boundaries which are absent in single crystals.

Typical calculations for an earlier chemistry of Rene N4, designated as VF 317 [5], were completed using the above equations imbeded in a twenty noded isoparametric brick. The combined constitutive equation and finite element was developed to model any piecewise linear load history and incorporated a dynamic time incrementing procedure. The calculated and experimental results are shown in Figure 1 for tensile tests at a constant strain rate of 8.33×10^{-5} sec^{-1} and three orientations. Tensile creep curves for seven specimens and the same three orientations is shown in Figure 2. The test temperature is 732°C which is close to the critical temperature and the maximum orientation effect.

LEVEL II MODEL DEVELOPMENT

The above combined constitutive and finite element model was successful for predicting both the orientation dependence and tension/compression asymmetry for tensile and creep histories. The model proved to be inadequate for fatigue due to its simplicity. In particular, there is no means of capturing both the short time strain hardening and the long term cyclic hardening observed in fatigue. Further, there is evidence that dislocations can pile-up at the γ-γ' interface at temperatures above the critical temperature. Thus, a set of local back stress state variables, similar to [6], have been incorporated into the model for both octhadedral and cube slip system. Further a set of computer programs have been written to evaluate the material parameters using a nonlinear optimization technique. The programs have been tested in a preliminary mode and they will be used in conjunction with the experimental program.

EXPERIMENTAL PROGRAM

The experimental program consists of approximately 50 tests at five temperatures, five orientations and several strain rates. In most cases the test will be stopped before failure to examine the active slip mechanisms in the strain range of interest. The work will primarily focus on monotonic tension at different strain rates and fatigue properties as a function of orientation. Creep will not be included in light of the above success with creep predictions. There will also be a group of nonstandard tests to evaluate the predictive capabilities of the model.

The initial phase of the experimental program is at 982°C (1800°F) since the earlier work was at 760°C (1400°F). This allows investigation of global strain resulting from the combined octahedral and cube slip mechanisms. The initial test matrix includes two tests each in the [001] and [111] orientations to isolate the octahedral and cube slip systems, respectively. The remaining tests are in the [123] and [110] orientations. This set of tests will be carefully evaluated before completing the test matrix at 982°C. The tests matrix for 760°C will be similar to that at 982°C. A few tests will be done at 1100°C, 870°C and 650°C.

These mechanical tests are being carried out on a closed loop MTS servohydraulic test frame. These are axial strain controlled tests in which load, axial strain and diametrical strain are monitored. An induction heating unit with microprocessor temperature controller is used for heating the specimens to temperature. Typically, the temperature was found to have a maximum gradient of 3°F through the gage length of the sample at 892°F. An example, the axial and diametrical stress-strain response of a specimen oriented in the [011] direction is shown in Figure 3. The diametrical extensonmeter is in the [01$\bar{1}$] direction. Notice that the elastic diametrical strain is positive which agrees with the values for the Poisson ratio shown in Figure 4.

REFERENCES

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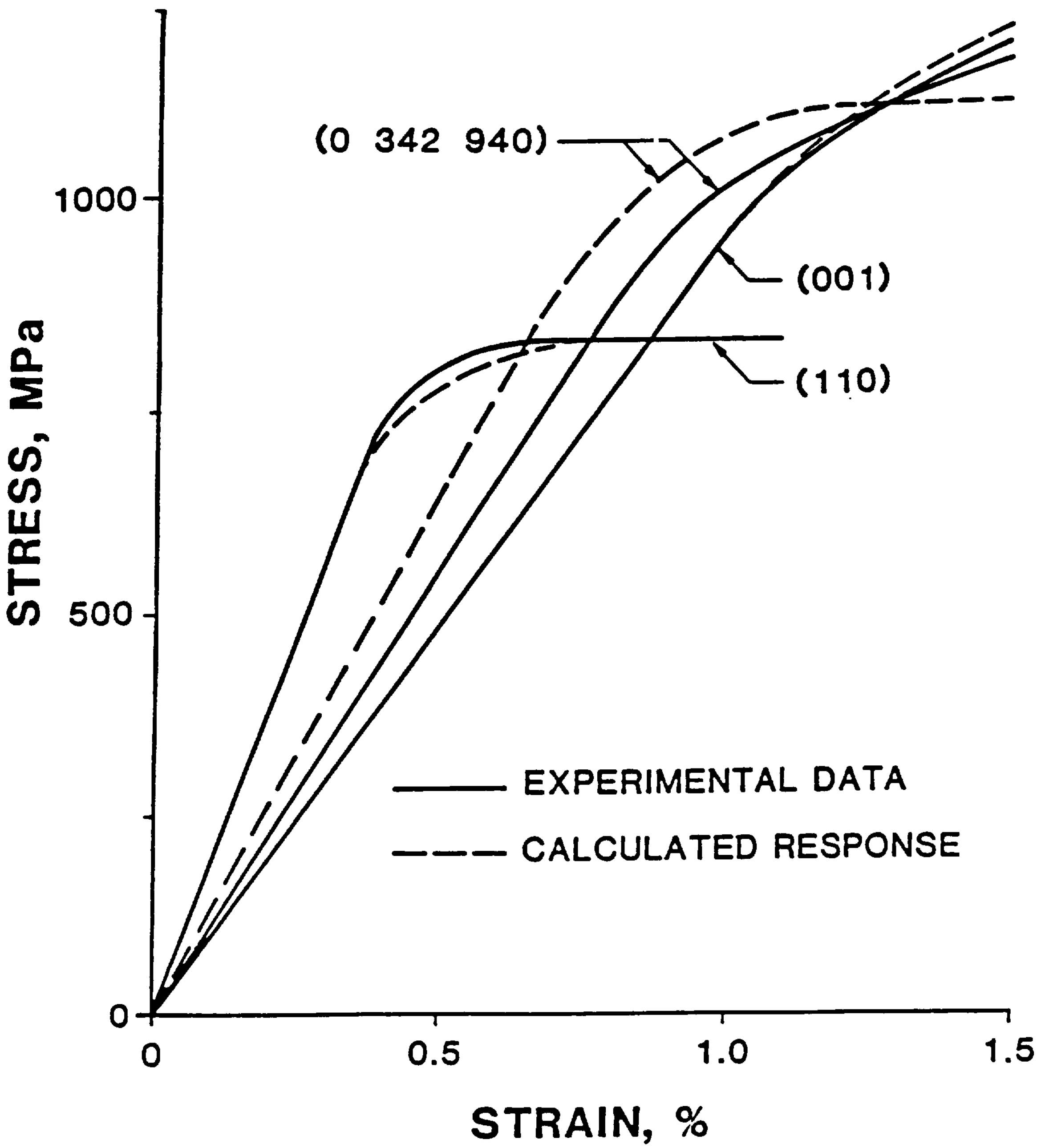

Figure 1. Predicted and experimental stress atrain curve for RENE N4 VF317 at 760°C.

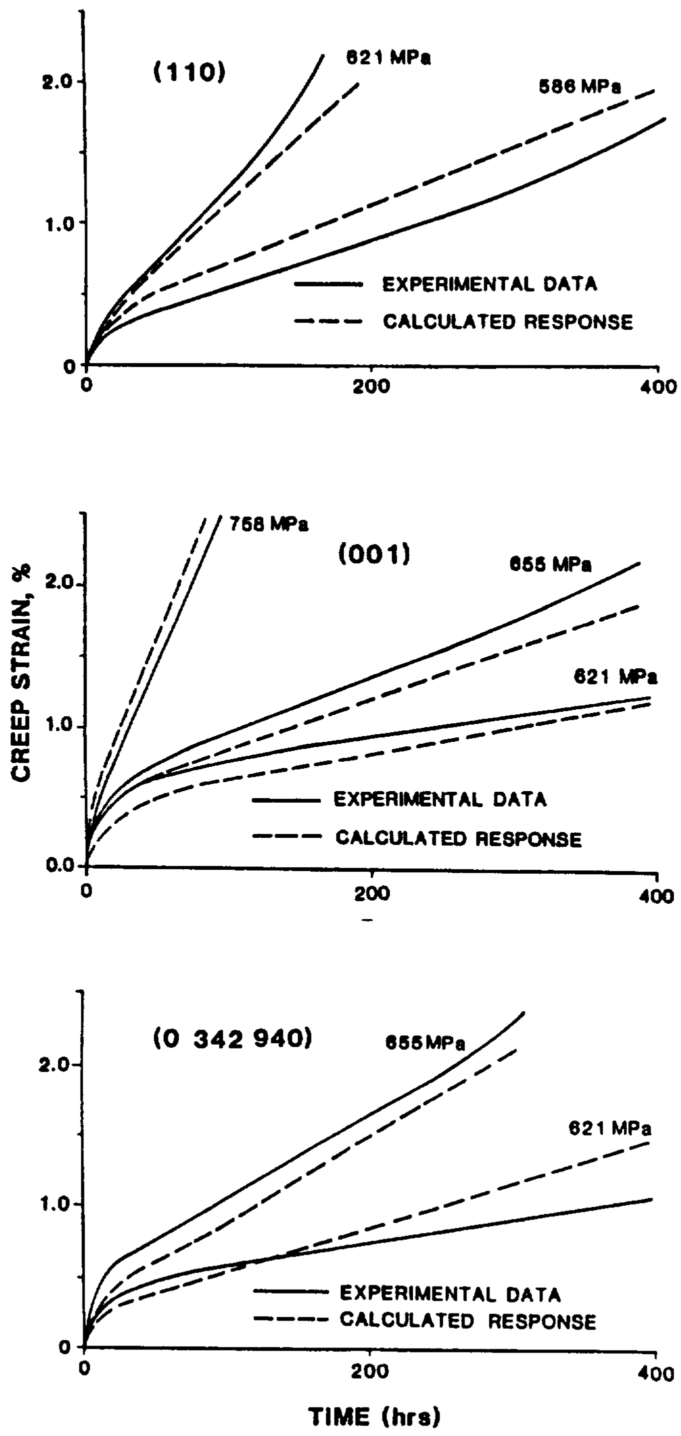

Figure 2. Predicted and experimental creep responses for RENE N4 loaded in different directions at 760°C.

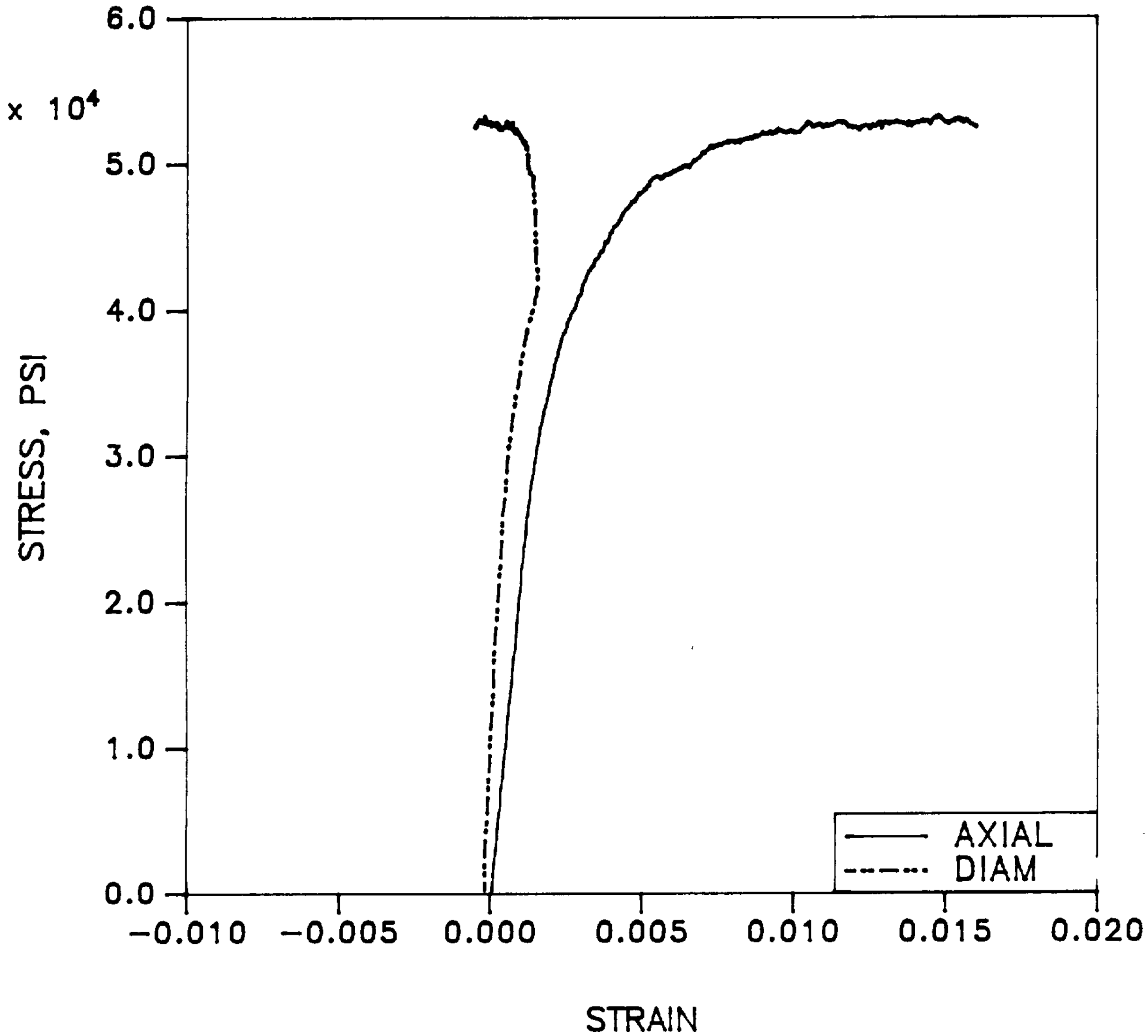

Figure 3. Tensile response of RENE N4 at 1800°F

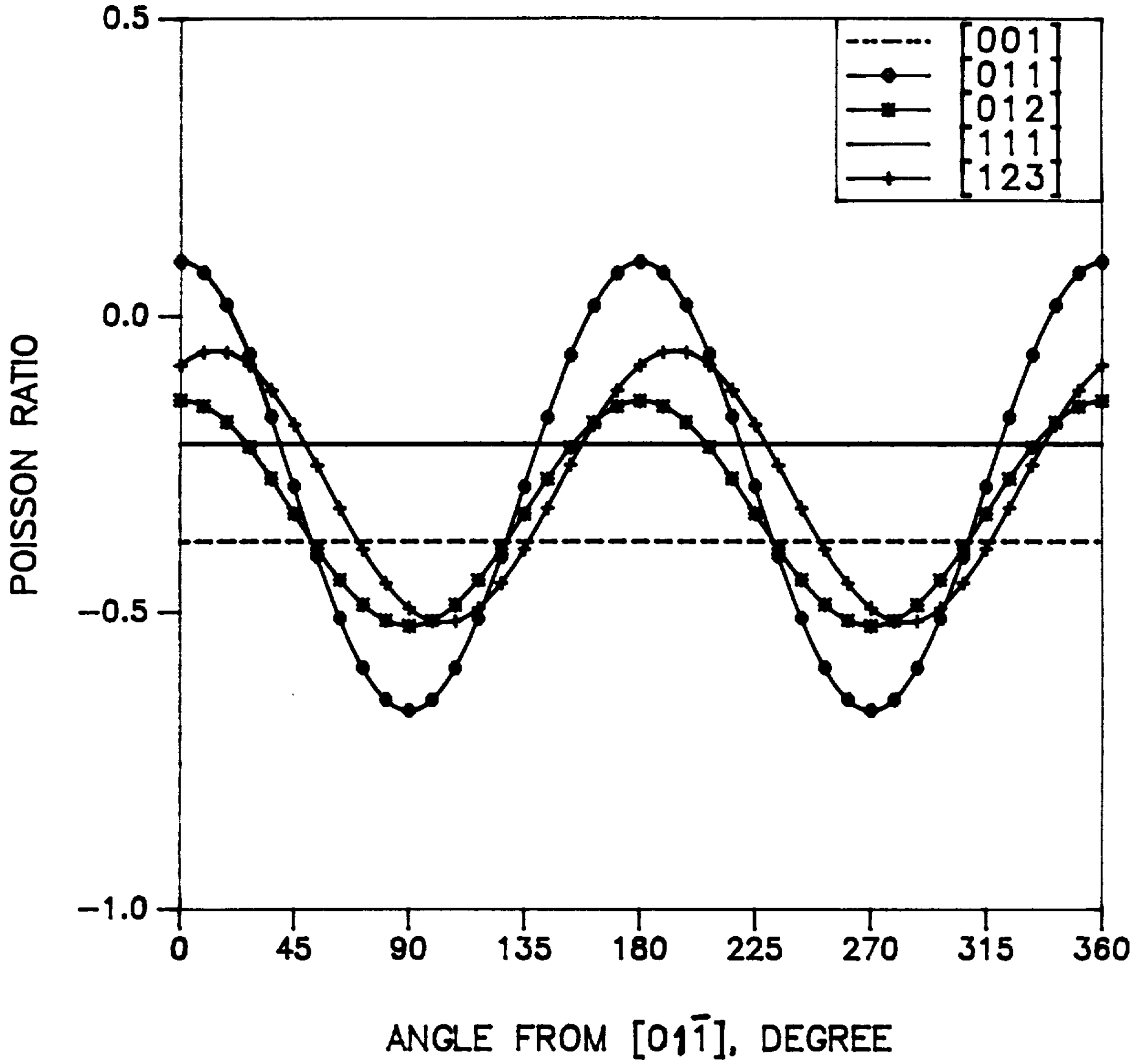

Figure 4. Variation in Poisson ratio with orientation for the five specimen orientations in the experimental program.